# Telemetry Tracking &Control (TT&C) – First TDRSS, then Commercial GEO & Big LEO and Now Through LEO


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## Abstract:

The advent of low earth orbit (LEO) commercial communication satellites provides an opportunity to dramatically reduce Telemetry, Tracking and Control (TT&C) costs of launch vehicles, Unpiloted Aerial Vehicles (UAVs), Research Balloons and spacecraft by reducing or eliminating ground infrastructure. Personnel from the Goddard Space Flight Center's Wallops Flight Facility (GSFC\WFF) have successfully used commercial Geostationary Earth Orbit (GEO) and Big LEO communications satellites for Long Duration Balloon Flight TT&C. The Flight Modem is a GSFC\WFF Advanced Range Technology initiative (ARTI) designed to streamline TT&C capability in the user community of these scientific data gathering platforms at low cost. Making use of existing LEO satellites and adapting commercially available components; two-way, over the horizon communications may be established with these vehicles at great savings due to reduced infrastructure. Initially planned as a means for permitting GPS data for tracking and recovery of sounding rocket and balloon payloads, expectations are that the bandwidth can soon be expanded to allow more comprehensive data transfer. The system architecture which integrates antennas, GPS receiver, commercial satellite packet data modem and a single board computer with custom software is described and technical challenges are discussed along with the plan for their resolution. A three-phase testing and development plan is outlined and the current results are reported. Results and status of ongoing flight tests on aircraft and sounding rockets are reported. Future applications on these platforms and the potential for satellite support are discussed along with an analysis of cost effectiveness of this method vs. other tracking and data transmission schemes.


## Introduction

TDRSS initially served as one of the early TT&C space based satellite networks designed to replace the need for multiple ground tracking systems with GEO satellites capable of routing signals in full duplex from a single central ground station. Then came the commercial version of TDRSS through such entities as INMARSAT and ARGOS. Customers are charged for service costs rather than investing in equipment or operations costs. The Low Earth Orbit (LEO) satellite commercial companies such as ICO GlobeCom, Iridium and Globalstar improve on the commercial purchase of data at lower cost through shared resources and distribution through the Internet. Cost leveraging is further exploited by numerous LEO non-spacecraft commercial services for data relay such as monitoring truck movement, gas pipeline flow, and aircraft in-flight email & FAX services. This paper presents "The Flight Modem" as an alternative to lowering spacecraft ground station and infrastructure costs while leveraging commercial COTS products to achieve scientific objectives.

The Flight Modem exists today as an Advanced Range Technology Initiative (ARTI) funded by the NASA Goddard Space Flight Center (GSFC) Space Operations and Management Office (SOMO). The Flight Modem is an enabling technology designed to bridge existing technology with commercial products and streamline missions with a more cost effective tool that eliminates the requirement for ground system and infrastructure support for tracking and command. The Flight Modem began as a concept to lower mission costs by leveraging advances in existing space based Internet Protocol (IP) communications for over the horizon (OTH) low bandwidth (< 9600 baud) data. There were many LEO satellite commercial companies to choose from. Only one offered global commercial IP space based communications with COTS Original Equipment Manufacturer (OEM) products to support full duplex and low bandwidth data requirements on a satellite constellation, Globalstar. The Flight Modem uses a GPS receiver and a Satellite Packet Modem compatible with the Globalstar satellite network. Field-testing with aircraft, sounding rockets and balloons has revealed other valuable applications that have the potential to reduce mission costs significantly. Small spacecraft use low rate command data at typically 2 kbps. The Globalstar link supports 9.6 kbps with greater global coverage than the existing ground and aircraft tracking systems such as the Advanced Range Instrumentation Aircraft (ARIA), P-3 Extended Area Telemetry System (EATS), and the E-9A Airborne Telemetry Platform.

The Flight Modem is undergoing three phases of testing; Phase I: Ground System Testing, Phase II: Aircraft Flight Tests, and Phase III: Sounding Rocket Test Flight. Phase I is the terrestrial based testing conducted with an early version of the Satellite Packet Modem called the tri-mode phone. These tests help establish latency measurements, Bit Error Rate (BER) testing, and software development of an automated dialup connection. Phase II are the aircraft test flights designed to test satellite handover, BER tests, and application data flows such as GPS and other airborne data. Phase III moves the Flight Modem into a sounding rocket test flight to conduct environmental testing, dual frequency wrap around antenna design, received satellite signal strength, and coverage at higher altitudes.

## Phase I: Ground System Testing

Phase I introduces a description of the flight modem and its components used during ground system testing. A comprehensive measurement of in and out of band emissions on the tri-mode phone and car kit follows. Peak power to level measurements and FCC/NTIA rules on Out-of-Band Emissions for Global Mobil Personal Communications (GMPCS) operating in the 1610-1660.5 MHz Band is then discussed.

**Flight Modem Description**

The Flight Modem was assembled around a phone before the availability of the satellite data packet modem. This system was assembled for aircraft flight tests while the more rugged modem card will be used for the rocket and balloon flight tests. Aircraft personnel have requested phone or voice capability for over the horizon communications. These phones will continue in the test program until the commercial aircraft kits similar to the already available car kits are available for purchase later this year (development has been announced in the press by commercial companies).

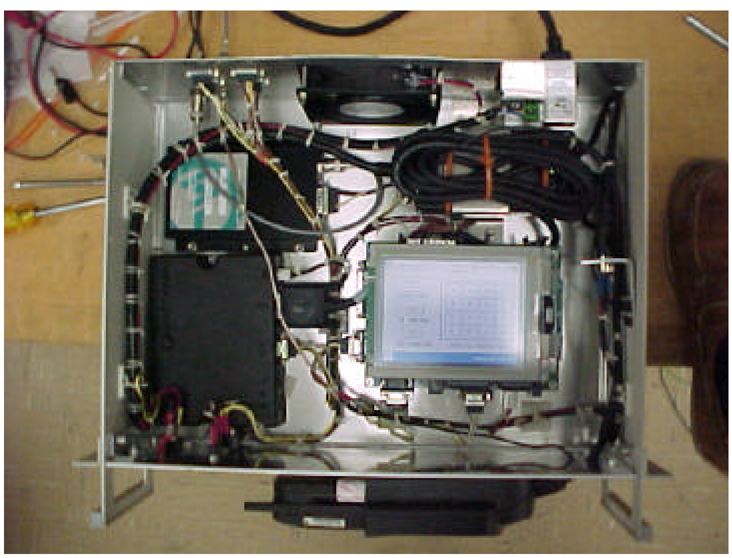

Figure #1 – Aircraft Flight Modem Top View of Components in the Chassis

Figure #1 shows the phone inserted in the Car Kit cradle mounted on the chassis front panel. The chassis height is 5.25 inches. The car kit cradle holds the phone with a mechanical locking system so that the phone can be removed for standalone operation. The tri-mode phone has a data cable for direct connection of a laptop without the car kit but this limits operation to 45 minutes of continuous operation using the battery charge of the phone. The car kit consists of (1) the phone cradle, (2) an auxiliary black box, (3) a separate private handset for use while the phone is in the cradle, (4) separate speaker and microphone for hands free operation, (5) a magnetic base car top antenna and (6) all required cables and wiring. The auxiliary black box contains an interface connector for a laptop through RS-232, 12V wire harness for connection to a car battery or other power supply, a 7dB power amplifier to boost the 1610-1625 MHz at 0.4W from the phone up to 2.0W, and RF interface connectors for cables to the phone and car top or aircraft antennas.

The front panel mounting is required for turning on phone power and monitoring the phone operation for preoperational checks. Normal flight tests of BER or GPS data transmission are hands free operation with turn on and preoperational checks before flight then turn off after flight. The red power switch can also turn off all power. Figure #1 shows the top view of the components mounted in the chassis. Figure #1 shows the car kit auxiliary black box in the lower left corner, the flight computer LCD screen in the lower right corner, and an internal GPS receiver in the upper left corner, and a power converter (110VAC to +5VDC and +12VDC) under its AC power cord in the upper right corner. The fixture at the upper right corner with the external power cord is the AC filter/fuse/connector unit.

When the new satellite data packet modem card is available, the Car Kit and tri-mode phone are no longer required. The modem is a single printed circuit card about 7"LX3.5"WX0.65"H and there will be only data capability with no voice. But, Voice Over Internet Protocol (VOIP) is likely to provide voice for the modem in the future. The Flight Computer display will also be deleted after software development and test is completed. The flight computer printed circuit board below the display is smaller than the display. The commercial aircraft antenna is 2.5"Wx3.0"Lx0.7"H. It contains a band pass filter on the receive antenna to reject the transmit antenna signal to protect the 2485-2500 MHz low noise amplifier (LNA).

**Duplex Communications**

The LEO satellite communications system must be treated as any other commercial telecommunications system such as the public switched telephone network (PSTN). Error free data flow is guaranteed whenever a connection is made. The User Terminal (UT) – a phone or satellite packet data modem – operates similar to cellular phones and modems. The UT cannot transmit until it receives a signal containing information on its allocated transmission frequency. A gateway is a satellite ground station that controls the RF transmissions between UT, satellites and voice or data to the PSTN.

The LEO communications system we have tested was designed for global coverage on the earth's surface and also for commercial airliner communications on a continuous basis. When the UT goes to higher altitudes than commercial airliners then limitations of the LEO satellite antenna beam-widths and satellite positions determine when a connection can be made.

Initial requirements for a vehicle locator system required only UT to science control center to send vehicle or UT GPS position data. However, the system, like a phone system is always full duplex or continuous two way. Tests were conducted for forward link (science center to UT), return link (UT to science center) and loopback (UT to gateway where the same data is then looped back to the UT for comparison). These tests were conducted with Pseudo Noise (PN) sequences used by most satellite telemetry pulse code modulation (PCM) links. Our conclusions after two months of tests were that the bit error rate tests (BER) always produced error free data for all configurations if a connection were made. And, connections were made as easily as a GPS receiver acquires its satellite signals and provides position data.

Recently, a satellite packet data modem Developer's Kit that provides information for third party developers to interface with the LEO system. This kit confirmed that BER techniques are used for forward error correction (FEC) and connection is terminated when the data cannot be corrected. FEC codes provide the number of corrected errors based on the error code regeneration so that corrected errors are a good measure available for ensuring quality of service before the user is subjected to degradation. Corrected error counts allow the LEO communications system to raise UT or gateway transmitter power level for better link margin or reduce power level to allow more UT signals through the satellite transponder.

Our BER tests included transmission of the data to and from the gateway through the Internet. Tests with a leased commercial data circuit to and from the gateway were cancelled due to the error free performance and low latency of the Internet.

**Latency Measurements**

Latency was measured by adding a time stamp to our transmitted data as it went to the UT then time stamping the received data. The difference between the two times is the latency. Latency included the UT transmission delays, UT to satellite delay, gateway delays, Internet delays and receiving equipment delays. Typical latency for the Wallops Island, VA BER data through the UT through the satellite and gateway and back to Wallops BER equipment was 25 milliseconds.

The latency appears reasonable when reviewing the transmission path. The laptop or BER data transfers into the UT at 33.8 kbs where it is buffered into a 9600 bps stream required for RF transmission. The data is transmitted continuously and the UT was able to accept continuous input of BER data for hours on end. Transmission from the UT to satellite at an altitude of 1440 kilometers (km) should be about 4 milliseconds (ms) but will vary as the range to the satellite moving in orbit. Since three or more satellites typically receive the UT signal the gateway stored the data from each path, time aligns the data and performs diversity combining to provide the best signal. This diversity combining eliminates satellite-to-satellite handover that ground stations must deal with due to horizon break or loss of line of sight for the signal. The diversity combining delay can be as high as 7 ms to accommodate signals from satellites overhead and on the horizon at the same time. Total latency is then about 2 ms for the UT low rate data buffers, about 4 ms from UT to satellite, about 4 ms from satellite to gateway, 7 ms or less for diversity combining, 6 ms for Internet and 2 ms for BER test set receiver to buffer the low rate data.

**Automated S/W dialup**

Commercial service is straightforward – plug in a laptop or PC running Windows 98 or later, enter the phone number of the gateway into the web browser then surf the web, send e-mail or FTP data like any other Internet connection. The gateway to Internet interface is seamless. The challenge is to perform the same functions on a flight computer that must read data from a GPS receiver or telemetry equipment, time stamp the data and make the dial up connection. Most flight computers do not run Windows 98. Windows CE was chosen as the likely candidate for simple implementation of dial up; but, the lack of documentation proved astounding. Fortunately, Windows CE Version 3.0 became available just before we were to choose a different operating system then trial and error techniques found the combinations of code to make dial up perform correctly. Starting with a different operating system may have been less time consuming.

The techniques for automating dialup connections, initiating TCP/IP connections, and reading/writing to serial communications ports are widely available for Windows 95/98/NT. However, Windows CE does not implement these techniques in the same manner as the other operating systems. The most likely source of programming techniques was obviously going to be the Microsoft Developer Network (MSDN) as it provides all of the techniques and guidelines needed to create programs under Windows CE. When using the MSDN, though, we found the information somewhat cryptic in nature and rather difficult to navigate. Techniques found in the MSDN were, for the most part, incomplete in their explanation of programming as they failed to mention other steps required before, after, or in addition to the current programming technique. After much research, we were able to locate and purchase a book called Windows CE 3.0 Application Programming [10]. This book explained, in detail, most of the steps required each of the techniques for our software. After much trial and error and the explanations in this book, we were eventually able to bring all of the pieces together and perform automated dialup and data transfer.

**BER Tests**

The Developer's Kit for the UT provides interface cables, documentation and software to read Received Signal Strength Indicator (RSSI), bit errors from the FEC corrected error count, number of bad frames (frames with corrected errors) and total number of frames received. In addition, control is provided to dial another phone number at the gateway to initiate a loopback test from the UT to the gateway and back to the UT. These tests demonstrated how well the system is controlled for quality of service. Our BER data sent through the system was always error free whenever a connection was made.

The Developer's Kit also has tools required for airborne and certain satellite users. The kit allows the UT to be configured to search for only designated gateways rather than all possible worldwide gateways to reduce search time for acquisition or reacquisition. This limited search is especially useful for sub-orbital rockets and aircraft flight tests. A couple of second's acquisition time is usually not a concern for satellites or balloons. Maneuvering aircraft causes rapid changes in antenna pattern orientation as well as dynamic Doppler frequency changes so that rapid reacquisition of the connection is critical to near continuous position information. Multiple radars are often deployed for these reasons. One example is a UAV and another is over the horizon (OTH) aircraft science data gathering where experiment control requires science information to control on-board sensors.

There is even more sophisticated control and monitoring capabilities available called the Diagnostic Monitor used by service technicians. These tools are licensed and sold only after Non Disclosure Agreement documents are signed. Use of these tools is neither necessary nor recommended because changing the system operation is a serious risk with so many activities highly interactive.

**In-Band Emissions**
A major concern for the in-band emissions is protection of the National Radio Astronomy Observatories (NRAO) that share the 1610.0-1613.0 MHz band with the Global Mobile Personal Communications (GMPCS) systems that include LEO satellite communications systems. Regulations provide protection zones around NRAO excluding GMPCS airborne transmissions in these zones during scheduled NRAO operations. In addition, GMPCS will take measures to preclude interference to NRAO operations. Code of Federal Regulations [1] CFR 47 Section 25.213(a)(1)(iv) has a formula of no airborne transmission within d^2 = 16.81(h) where d is the ground distance in kilometers between the airborne vehicle and NRAO antenna and h is the airborne vehicle altitude in meters. These concerns do not apply to satellites because path attenuation is great. This concern is for nearby airborne vehicles.

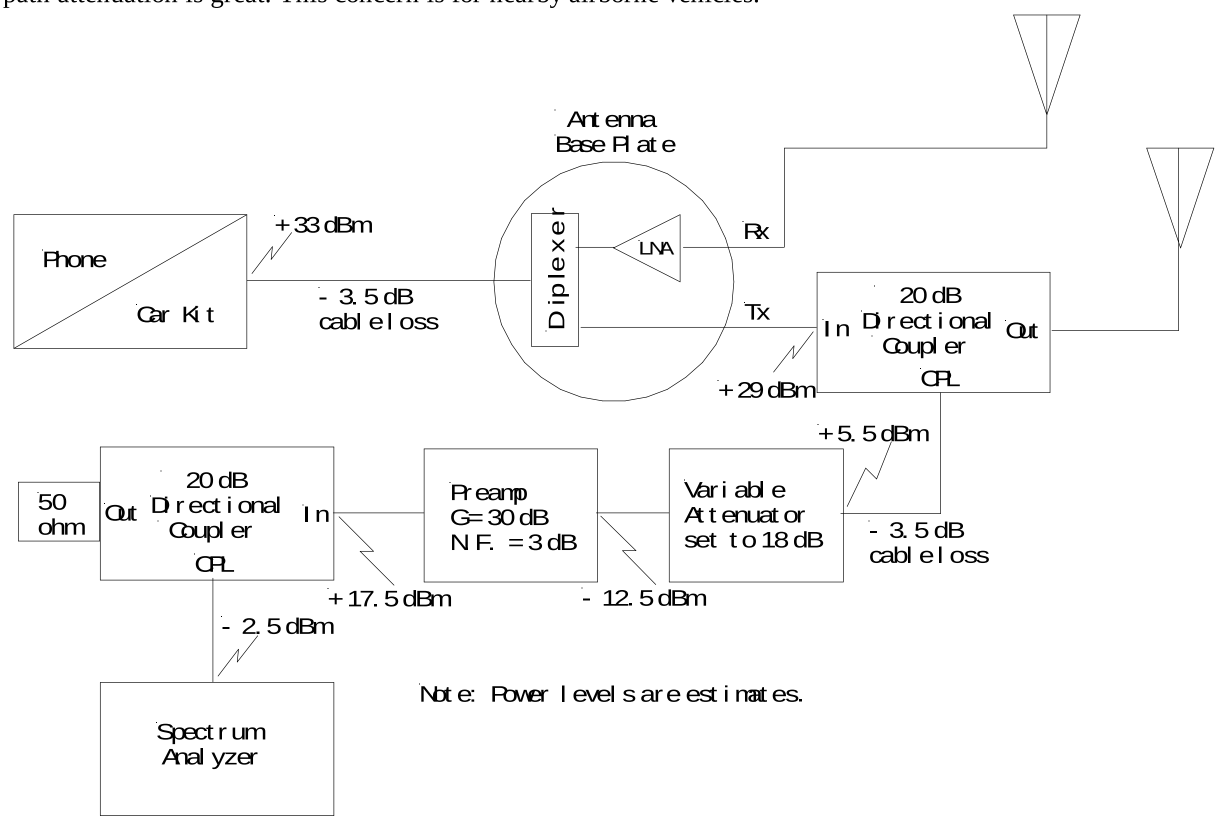


Figure #2 - Globalstar Emissions Measurement Configuration

Figure #2 shows the test configuration used to measure Globalstar emissions. A continuous transmission of pseudo noise (PN) bit error rate (BER) data was made through the Globalstar system to a Programmable Telemetry Processor (PTP) that received and verified the data. The PTP counted bit errors, bytes received, frames received and displayed the IP socket connection status. Zero bit errors were observed whenever the socket was connected. An occasional single bit error would occur when the socket connection was made or broken. Socket connection was usually lost only when the operator terminated a connection to change RF cable configurations for calibration signals.

The transmitted power level generally remained, on average, very constant due to the continuously repeated BER data sequence. The spectrum shows this uniform distribution of an equal number of ones and zeroes of the pseudo noise (PN) code. Typical data or voice would have constant levels and frequency distribution in bursts that would appear as widely varying levels and frequency distribution and not allow this clear spectrum display. Data and voice signal spectrums were observed to always lie in the assigned 1.23 MHz channel at levels equal to or lower than the PN code. If the spectrum analyzer could capture short burst transmissions, then the spread spectrum looks like our continuous transmission spectrum plots. Figure #3 shows the BER PN code modulating the spread spectrum carrier at 1617 MHz. Note the signal width is 1.23 MHz as described in [2] and [3]. The bit rate is 9600 bps modulating a 614,400 chip per second rate to produce Code Division Multiple Access (CDMA) or spread spectrum. The symbol rate is Quadrature Phase Shift key (QPSK) modulated on one carrier in the 1610-1625 MHz band. Thirteen carriers are selectable in the assigned band. The selected carrier frequency is chosen in real-time, based on carriers already in use and remaining frequency assignments available, by the Globalstar gateway or ground station. Power level of the User Terminal (UT) is frequently adjusted by the gateway as it monitors received signal level from the UT.

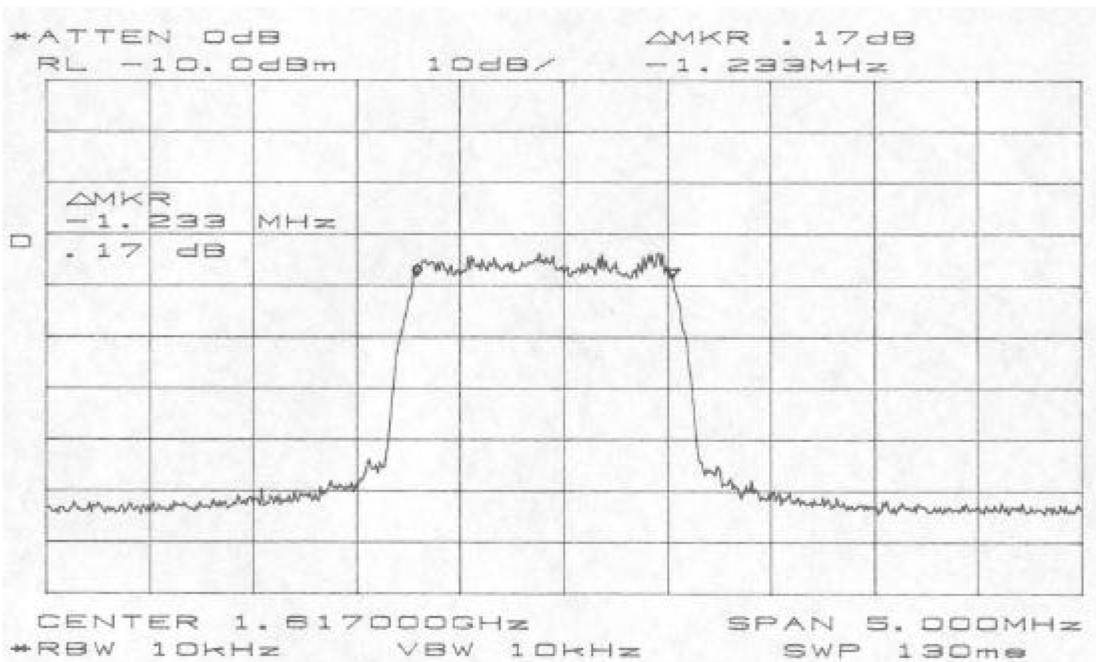


Figure #3 - Globalstar In-Band Emissions

**Out-of-Band Emissions**

NASA and NTIA requested Globalstar out-of-band emission measurements in terms of Effective Isotropic Radiated Power (EIRP) to determine possible interference to nearby Radio Navigation receivers in the 1559 to 1605 MHz band. The following measurements are not EIRP, which requires measurement of radiated signals through an antenna with a receiving antenna. Those tests are planned with the nearly hemispherical aircraft antennas. Some GPS and mobile satellite communications antennas attempt to optimize gain at the horizon where the satellites will be at maximum range and accept lower gain at zenith due to the closer range. High performance mobile antennas can provide + 3 dBi gain near the horizon with – 3 dBi gain at zenith. Average mobile antennas often provide only 0 dBi gain near the horizon with – 6 dBi at zenith. The transmitter output measurements should be fairly representative of the expected EIRP due to the nearly uniform, close to unity antenna gain.

Additional tests are planned to measure how close the Globalstar transmit antenna can be placed to a GPS receive antenna before degradation of the GPS performance is observed. Preliminary results show no significant GPS degradation when the antennas are six inches apart for our flight rated equipment. Our GPS LNA contains a measured 15 dB out-of-band rejection at 1575 MHz +/- 35 MHz.

Figures #4 through #7 show the transmit signal measured at the aircraft antenna transmit connector. A 35 foot cable between the Flight Modem chassis and the antenna base plate, another 35 foot cable between the 20 dB directional coupler at the antenna and the fixed attenuation of the 20 dB directional coupler at the spectrum analyzer prevented overdrive of the analyzer input. A low noise preamplifier was inserted in front of the spectrum analyzer to reduce the spectrum analyzer noise contribution. A variable attenuator was placed in front of the preamplifier to prevent saturation of the amplifier by the Globalstar transmitter signal. This variable attenuator was adjusted for maximum signal to noise ratio with at least 10 dB difference between transmitter out-of-band noise level and spectrum analyzer noise level with no analyzer input.

The spectrum analyzer span was selected to display both the 1159-1605 MHz Radio Navigation band and the Globalstar 1610-1615 MHz band. Spectrum plots at resolution bandwidths of 1 kHz, 3.0 kHz, 10 kHz and 1.0 MHz were made in single sweep clear/write trace mode then again in Max Hold trace mode to look for spurious signals. Only the Max Hold mode pictures are provided in this paper. The spectrum analyzer displayed “uncalibrated” when the resolution bandwidth was set to 1 kHz but no out-of-band spurious signals were observed at this setting. The expected differences in signal levels for the five RBW in Figures #4 through #7 are in close agreement with theory (e.g., 10log(1 MHz/10 kHz) = 20 dB).

The signal to noise ratio (Ps/Pn) when the carrier level is measured identifies the suppression of out-of-band emissions to this minimum level. Table 1 is a summary of peak power readings from Figures #4 through #7. A difficulty in comparing one figure to another is due to the small changes in power level of the UT as it is controlled by the gateway. Another difficulty is operation of the spectrum analyzer near its maximum input level before gain compression in order to obtain maximum measurement range of signal to noise ratio. On the other hand, each figure can stand alone as a valid measurement of transmitted signal to noise at that time. And, the transmitted peak level is also available on the plot.

Table 1 – Peak Power to Peak Noise Levels from the Globalstar Transmitter

| Figure Number | Resolution Band Width | Peak Signal Power | Peak Noise Power | Ps/Pn |
|---|---|---|---|---|
| #4 | 1 MHz | - 6 dBm | - 67 dBm | 61 dB |
| #5 | 10 kHz | - 20 dBm | - 90 dBm | 70 dB |
| #6 | 3 kHz | - 24 dBm | - 96 dBm | 72 dB |
| #7 | 1 kHz uncal | - 25 dBm | - 100 dBm | 75 dB |

One of the most interesting features of the table is the peak power level increase as Resolution Bandwidth (RBW) is increased. As RBW is increased more of the signal power is contained in the RBW which approaches the average power level then equals the average power level when all the sidebands are contained in the RBW (i.e., when the RBW is equal to or greater than 1.23 MHz). For the 1 MHz RBW the peak and average power should be very nearly the same.

Average power in Figure #4 should equal the unmodulated carrier power level that is close to – 6 dBm. This level, as estimated in Figure #2, is roughly confirmed by an 2.0W (or +33 dBm) maximum transmitted power minus 3.7 dB cable loss to the antenna base plate minus 20 dB directional coupler loss minus 3.7 dB cable loss to the directional coupler at the spectrum analyzer minus 2 dB miscellaneous connector and short cable losses equals -1.6 dBm. The difference between –1.6 dBm and the peak measured power of – 6 dBm in 1 MHz RBW could be the gateway power level control.

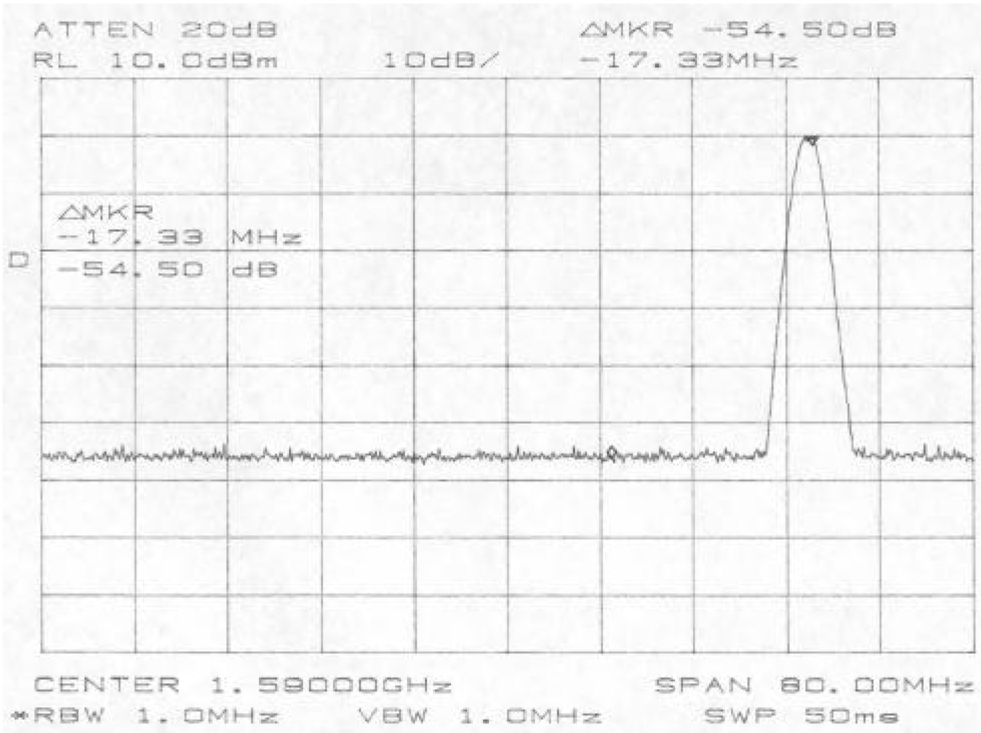


Figure #4: Globalstar Out of Band Emissions

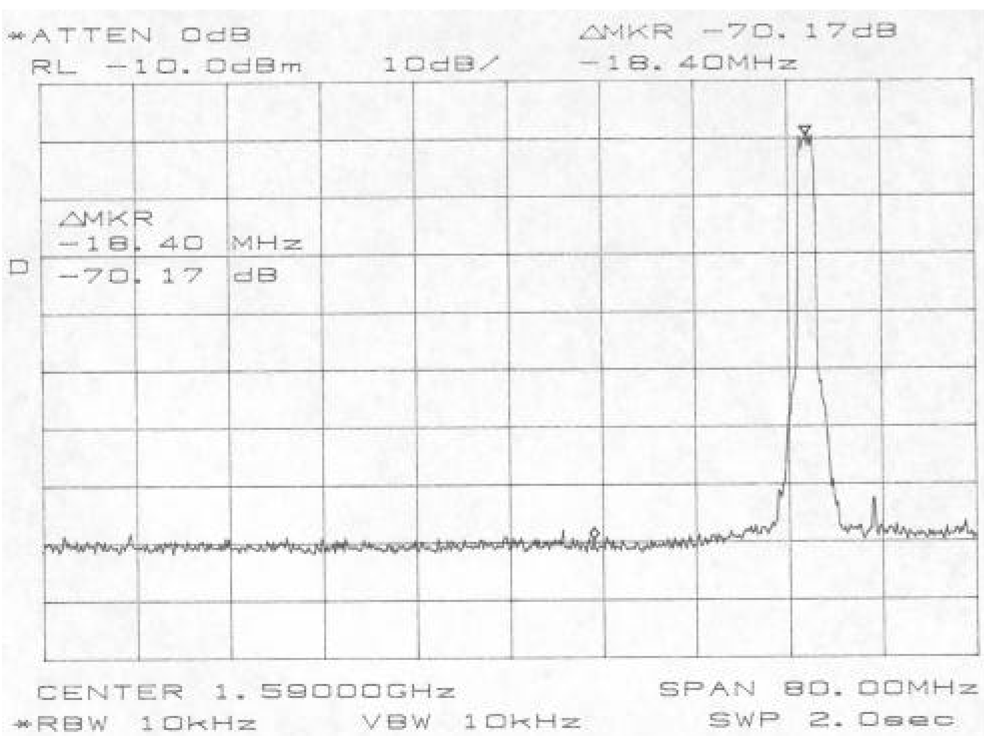


Figure #5 - Globalstar Out-of-band Emissions

The unmodulated Ps/Pn in 10 kHz RBW of Figure #5 is then 70 dB + 20 dB = 90 dB. Therefore, out-of-band emissions are equal to or less than 90 dB below the unmodulated carrier because no out-of-band emissions are observed above the analyzer noise level. The transmitter output should be 2.0W or + 33 dBm then the maximum out-of band emissions are 33 dBm – 90 dB = -57 dBm = - 87 dBW/10 kHz = - 67 dBW/MHz. The 2.0 second sweep time for 80 MHz = 25 milliseconds per MHz or 0.3 ms per 10 kHz.

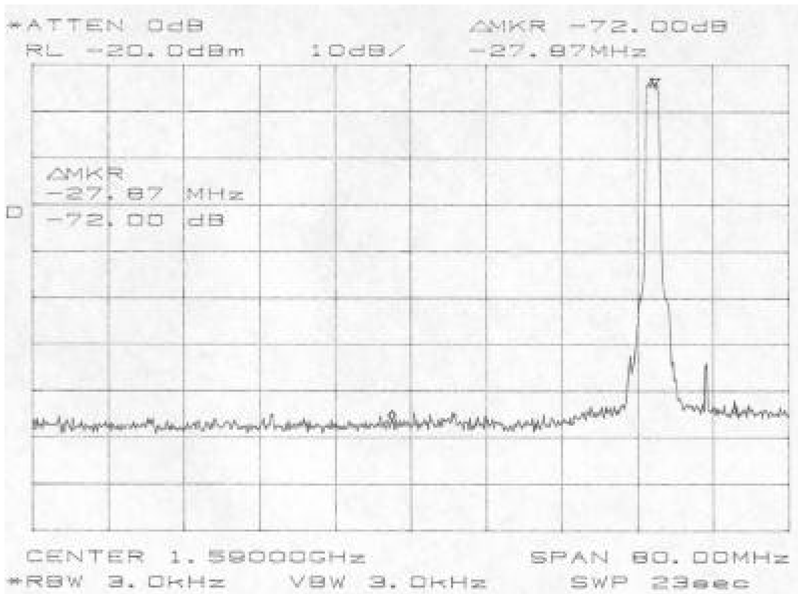

Figure #6 - Globalstar Out-of-band Emissions

The unmodulated Ps/Pn in 3 kHz RBW of Figure #6 is then 72 dB + 25.2 dB = 97.2 dB. Therefore, out-of-band emissions are equal to or less than 97.2 dB below the unmodulated carrier because no out-of-band emissions are observed above the analyzer noise level. The transmitter output should be 2.0W or + 33 dBm then the maximum out-of band emissions are 33 dBm – 97.2 dB = -64.2 dBm = - 94.2 dBW/3 kHz = - 69 dBW/MHz. The 23.0 second sweep time for 80 MHz = 287.5 milliseconds per MHz or 0.9 ms per 3 kHz.

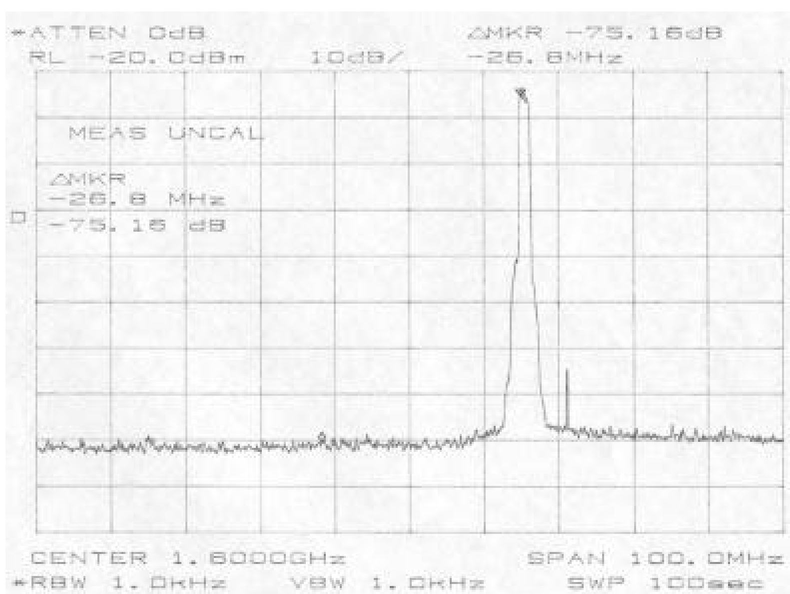


Figure #7 - Globalstar Out-of-band Emissions

The unmodulated Ps/Pn in 1 kHz RBW of Figure #7 is then 75 dB + 30 dB = 105 dB. Therefore, out-of-band emissions are equal to or less than 105 dB below the unmodulated carrier because no out-of-band emissions are observed above the analyzer noise level. The transmitter output should be 2.0W or + 33 dBm then the maximum out-of band emissions are 33 dBm – 105 dB = - 72 dBm = - 102 dBW/1 kHz = - 72 dBW/MHz. The 100 second sweep time for 100 MHz = 1000 milliseconds per MHz or 1 ms per 1 kHz.

Obviously, calibration of the spectrum analyzer measurements will not allow selection of the RBW and sweep times (1 MHz RBW averaged over 20 ms or 20ms/MHz sweep time and 700 Hz RBW with sweep time of 20 ms) as required by NTIA and FCC for their regulations listed in the next section. Computation for conversion of the measured data to the desired RBW and averaging time must be made. Better measurement techniques or equipment are required to measure the levels listed in the regulations. Plans are in progress to make refined measurements.

**Out-of-Band Emissions Summary**

Out-of-band emissions are below our current capability to measure. The very low level of the out-of-band emissions in our measurements confirm good engineering practices were followed to reduce out-of-band emissions and provide confidence that the final improved measurements will confirm the proposed FCC and NTIA regulation requirements are met. Improved measurement techniques are being prepared to measure the out-of-band emissions with the simplest configuration to filter out the 1610-1625 MHz band then feed the remaining transmitter output through a preamplifier that feeds the spectrum analyzer.

**FCC/NTIA rules on Out-of-Band Emissions for GMPCS operating in the 1610-1660.5 MHz Band**

FCC and NTIA documents of proposed regulations and measurement methods for out-of-band emissions in [4] and [5] are constantly being updated due to ongoing discussions with industry and the International Telecommunications Union (ITU). The highlights of regulations pertaining to this project are listed below and were the guide for making measurements shown above.

[5] describes of how NTIA and JHU/APL measure GPS interference and their results that show the pulse width of the interferer is the primary concern. NTIA documents where JHU/APL performed studies for the government show that the 500 symbols/sec of GPS (1/T = 20 ms) is more susceptible to long duration pulse interference than short duration pulse interference. Ultra Wideband transmissions caused less interference with their high data rates than Narrow Band transmissions at low data rates. These studies were a primary reason for the proposed regulations of - 70 dBW/MHz averaged over 20 ms EIRP and - 80 dBW/700 Hz averaged over 20 ms EIRP for out-of-band emissions from Global Mobile Personal Communications Systems (GMPCS). NTIA published their test plan on 14 June 2000 at web location in [6].

The NTIA test plan basically tells the parameters they will measure and that they will purchase the new test equipment on the market to develop the details of the procedures. The new test equipment is required to measure burst data. Specification of the parameters to be measured is the strong achievement of the plan. Specific interference tests and emissions tests in terms of both Power Spectral Density (PSD) and absolute transmitted power levels measured in specific bandwidths with specific averaging times are described.

“ Federal Communications Commission FCC 99-37 Proposed Amendment of Parts 2 and 25 to Implement the Global Mobile Personal Communications by Satellite (GMPCS) Memorandum of Understanding and Agreements and petition of the National Telecommunications and Information Administration to amend Part 25 of the FCC Rules to Establish Emissions Limits for Mobile and Portable Earth Stations Operating in the 1610-1660.5 MHz Band

Section 26.216 *Limits on Out-of-band Emissions from Terminals Operating in the 1610-1660.5 MHz Band for Protection of Aeronautical Satellite Radionavigation*

(a) *Limits on Emissions Below 1605 MHz.*

(4) As of January 1, 2005 and from then on, the e.i.r.p. density of emissions from mobile Earth terminals placed in service prior to January 1, 2002 with assigned frequencies between 1610 MHz and 1660.5 MHz shall not exceed -70 dBW/MHz, averaged over 20 ms, in the 1559-

1605 MHz band, and the e.i.r.p. of spurious emissions of less than 700 Hz bandwidth from such terminals shall not exceed -80 dBW, averaged over 20 ms, in that band. "

**Comparisons of measurements, rules and measurement parameters**
Measurement configuration improvements are required to verify the very low levels of – 80 dBW/MHz in a 20 ms average time and – 70 dBW/700 Hz in a 20 ms average time. The next method of measurement is to feed the transmitter into a 1610-1625 MHz band reject filter to reduce the carrier level without reduction of the out-of-band emissions. Without this rejection filter the spectrum analyzer must measure from + 33 dBm down to –80 dBW/700 Hz = -50 dBm/700 Hz for a measurement range of + 33 dBm – (-50 dBm/700 Hz) = 83 dB. A 1610-1625 MHz rejection filter of at least 60 dB rejection is being procured.

## Phase II: Aircraft Flight Tests

Phase II discusses the NRAO RF protection zones and the concern for frequency interference when flying aircraft that use the Flight Modem transmit frequencies close to NRAO bands. The Tyndall AFB E-9A is introduced as the first aircraft platform, and a discussion on aircraft antenna locations follows. Issues and resolutions experienced during data flows through the Flight Modem at the Tyndall AFB are then detailed. Results of the E-9A Sea Surveillance Radar (SSR) data integration with the flight modem are addressed, and future plans for aircraft platform testing at high altitudes and UAV applications follow.

**NRAO Protection Zones**
An important step in planning aircraft flight tests is verification of the NRAO protection zones. At Tyndall AFB, the aircraft maximum altitude is 25000 feet or 7620 meters resulting in d = 358km = 222.4 statute miles = 195.7 nm. This minimum distance of 358 km from a radio observatory for operation in the 1610.0-1626.5 MHz band on an airborne platform is easily met. For the most north and most west tip of the Tyndall AFB flight area over the Gulf of Mexico and a most north and most east tip of the flight area the two closest radio observatories in CFR 47 Section 25.213(1) Protection zones are Ft. Davis, Texas and Green Bank Telescope, West Virginia. The Texas observatory is more than 1463 km (800 nm) from the closest part of the Tyndall AFB Gulf test area and the West Virginia observatory is 1097 km (600nm) from the closest part of the Tyndall AFB Gulf test area. Both observatories are more than three times the required distance before the observatory operating schedule must be checked for periods of operation. However, coordination soon showed that NRAO prefers to monitor the aircraft operations with their more sensitive sites in New Mexico and Puerto Rico.

The NRAO frequency manager provided the following guidelines on their operations in the 1610-1613 MHz band during discussions on NRAO monitoring of our GMPCS transmissions during the aircraft flights: "The Very Long Array (VLA) and Very Long Baseline Array (VLBA) radio receiver front ends are wide open, on the order of 500 MHz to 1GHz, depending on center frequency. After a series of amplifiers and bandpass filters the VLBA can output a total of eight 16 MHz Intermediate Frequencies (IF). A typical IF bandwidth used is 16 MHz. The minimum selectable bandwidths are on the order of a kHz, depending on the observation."

**Tyndall AFB E-9A Background**
The USAF houses an inventory of only two E-9A aircraft of which both are stationed along the Gulf of Mexico in Panama City, Florida, at the Tyndall AFB. The E-9A is a modified Dehaviland Dash 8 instrumented with a telemetry relay subsystem, an ultrahigh frequency (UHF) voice relay subsystem, radar sea surveillance, and a Gulf Range drone control relay data link subsystem. The E-9A contains a flat plate phased array antenna equipped with 140 low noise amplifiers (LNAs) for airborne over the Horizon (OTH) communication relays.

The E-9A provides airborne telemetry and command relay communications for over the Horizon (OTH) data and voice communications during weapons evaluation missions. Additionally, the E-9A is capable of locating an over-water range area clear of boats for missile launches commonly called the shoot box with its sea surveillance radar (SSR) system in support of missile launch evaluations. These capabilities produce an ideal aircraft platform to test the concepts of OTH packetized IP data communications for the flight modem project.

**Antenna Locations**

An active hemispherical LEO patch antenna will mount on top of the nose of the E-9A. This location presents a 15–degree inclination on the ground and a 5-degree inclination in flight. A former landing light was used in this position and was removed after E-9A modifications. This location eliminates the need to puncture any portion of the E-9A frame and makes use of an existing mounting structure. Figure #8 depicts where the antenna will be located while Figure #9 indicates where the GPS antennas are located for the Universal Navigational System (UNS), UNS-950.

**Tyndall AFB (E-9A) Aircraft Tests**

The Tyndall AFB flight tests from Panama City, FL, will verify data transmission quality by traversing a course over 250 by 250 miles off the coast of Florida in the Gulf of Mexico with an E-9A aircraft. These tests will demonstrate diversity combining of many multiple satellite signal configuration changes due to satellite orbits. Tyndall E-9A test flights will test the performance of the Globalstar LEO communications system to acquire and track RF signals under low rate Doppler conditions with higher rate Doppler during aircraft change of course in a zigzag pattern. Data flows are to include on-board generated PRN 2^11-1 patterns, SSR, and GPS data through the LEO satellite network using the data enabled tri-mode phone and an embedded RLC Windows CE computer. Data will be recorded at NASA's WFF while SSR data is to be displayed locally at the Tyndall AFB. Latency will be recorded as reference from on-board time stamp to ground display. Full loop-back tests of data from the WFF to the aircraft and retransmit back to the WFF will demonstrate uplink as well as downlink data transmission quality.

Physical and electrical integration checks of the Flight Modem with the USAF 53rd Weapons Evaluation Group (WEG) E-9A Aircraft were made in October 2000. The small (2.5"W X 3.0"L X 0.7"H) aircraft antenna for LEO satellite communications is at least 6 ft. away from the GPS receive antenna locations depicted in Figure #8. The system is fully automated with the ground crew turning on the unit and selecting the desired mode – GPS data, Sea Search Radar data, etc for transmission – prior to taxi for takeoff. After landing the unit is turned off by the ground crew. Figure #10 shows the aircraft data flow diagram.

Figure #8: Flight Modem Antcom Globalstar antenna location


Figure #9: E-9A GPS antenna locations

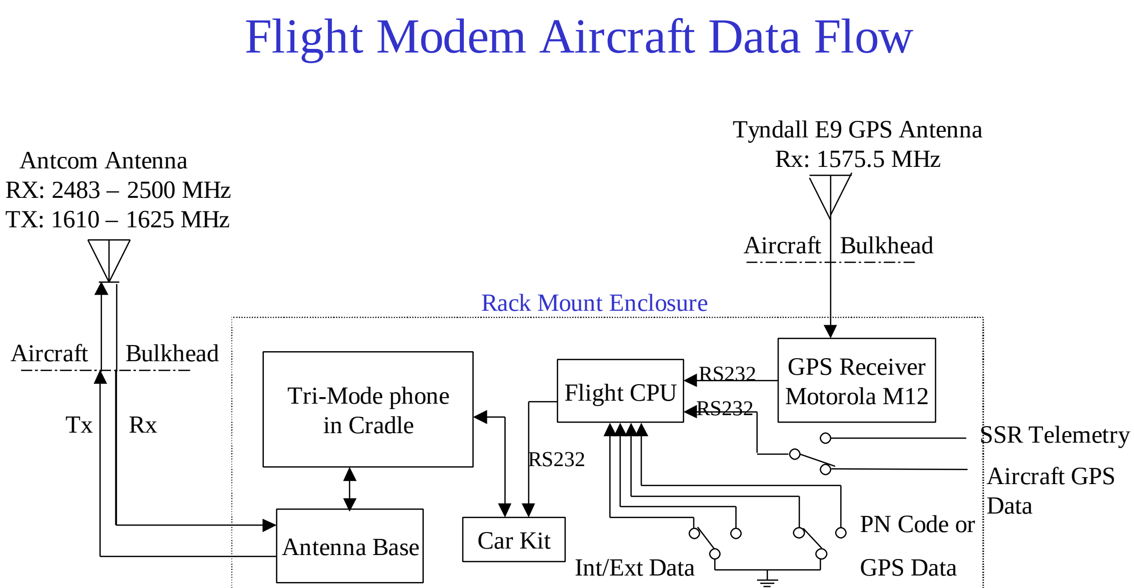


Figure #10: Flight Modem Aircraft Data Flow Diagram

**PRN Data flow from Tyndall AFB to WFF PTP**
A laptop computer was used to generate a pseudorandom (PRN) 2^11-1 pattern into the Qualcomm GSP1600 tri-mode phone. Data was then transmitted in IP packetized format via the Globalstar satellite network to a NASA/GSFC/WFF programmable telemetry processor (PTP) from the Tyndall AFB.

**PRN Data flow local to the Tyndall AFB**
An attempt was made to data stream PRN 2^11-1 data from a laptop through the flight modem and to a local Tyndall AFB PC. Tyndall AFB PCs use a dynamically assigned IP address for all incoming IP data. Data enters Tyndall AFB through a proxy server then translated and distributed to local PCs on base. Globalstar requires static IP destinations rather than randomly assigned IP addresses. We were able to secure a 3-day static IP address, but the proxy translation and firewalls prevented any coherent data streaming to a local Tyndall AFB PC. King Aerospace is contracted to maintain E-9A operations, and is working with the Communications Squadron to establish a secure open port for the flight project.

**E-9A SSR data interfacing to the Flight Modem**
A cable was strung from the RS422 outputs of the Sea Surveillance Radar (SSR) system to an RS422 to RS232 converter box. The RS232 output was then connected to the flight modem laptop for testing. Data was streaming into the flight modem laptop at 110 baud and bursted once a minute. A HyperTerminal on the laptop confirmed clean receipt of all data. King Aerospace gave us a sample file to develop software to format the SSR data into IP packets.

**Future Aircraft Test Plans**
Tyndall AFB flights will be conducted February – June 2001. Data collected and recorded will be used to measure the Globalstar data quality link with BER data flow and frame drop out measurements. The Dryden Flight Research Center (DFRC) ER-2 and DC-8 aircraft will traverse the continental US from Edwards AFB to the WFF. Planned testing is to include procedures and limitations for gateway handovers during data flows, latency and BER measurements. The NASA/GSFC/WFF P-3 aircraft will be used to conduct similar tests to the Tyndall AFB E-9A and DFRC aircraft. The WFF P-3 covers a large area off the east coast of Florida enabling coverage limits to be determined in Spring 2001.

## Phase III: Sounding Rocket Test Flight

A piggyback sounding rocket test flight in conjunction with Swedish Space Corporation (SSC) will offer the opportunity to measure the altitude and Doppler limits of the LEO satellite constellation communications. The rocket altitude of 100 km exceeds the satellite constellation designed support altitude for commercial airlines. Loss and return of connection is possible as the payload parachutes back to earth. The rocket trajectory will cause Doppler frequency changes exceeding the 3 kHz differential Doppler capability of the satellite communications system for acquisition and tracking during portions of the flight. The capability to track differential Doppler frequencies less than 3 kHz will also be demonstrated. The environmental conditions for temperature, vibration, shock and acceleration are met by the rugged construction and mounting of the equipment. Preflight environmental tests will confirm readiness then the flight will confirm the performance.

**Limitations**
There are numerous European gateways in operation for voice only. Data equipment is being added to these gateways as quickly as negotiations with local telephone companies can be completed on customer data rate charges. Data rate charges were agreed in December 2000 for the U.S. and these rates may offer a model for the European negotiations. The In-Flight Network (IFN) through our current LEO satellite constellation service provider is scheduled to begin commercial airline operations in Europe on April 1, 2001 (shortly after our launch). There are three gateways particularly well suited for the sounding rocket launch support near Kiruna, Sweden – near (1) Karkilla, Finland, (2) Paris, France, and (3) Moscow, Russia. These sites will not be available for IP data enabled packet trails for our first sounding rocket launch opportunity.

# Flight Modem Sounding Rocket Data Flow

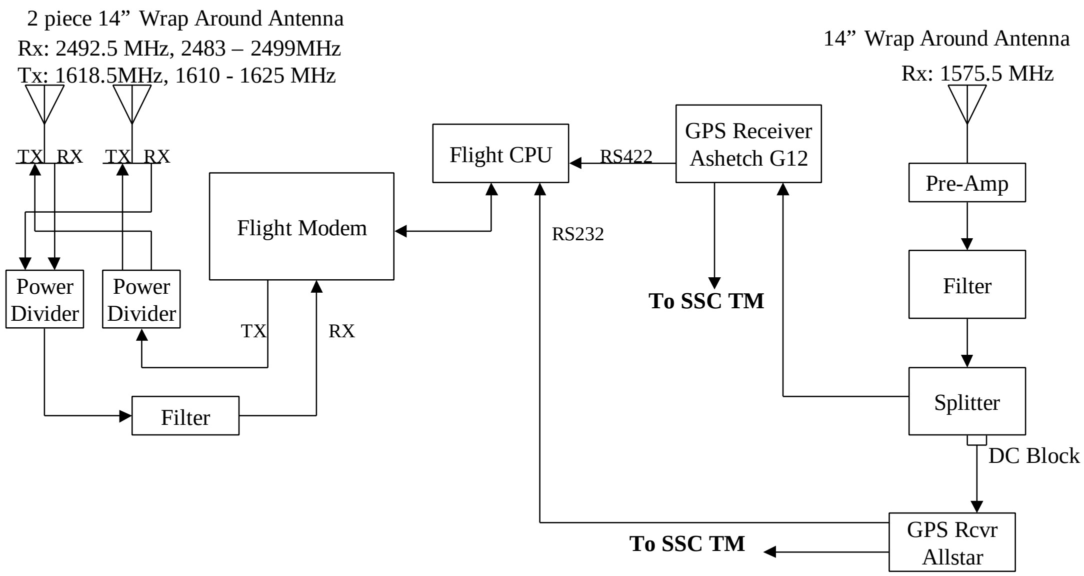


Figure #11 Flight Modem Sounding Rocket Data Flow Diagram

**Intended Measurements**

The Flight Modem GPS receiver data and the primary flight related GPS receiver data will be logged on the flight computer hard drive. The flight computer will dial up the voice gateways and make loop back tests to log satellite received signal strength indicator (RSSI), error count, and bad frame count for corrected errors and total frame count. If a data enabled gateway is available, GPS data will be transmitted in real-time through the LEO satellite constellation and logged. Figure #11 illustrates the data flow structure of the Sounding Rocket test flight with the Swedish Space Corporation (SSC).

## GPS

**GPS and Sounding Rocket History**

Civilian experience with GPS receivers on launch vehicles began in April of 1994 with inclusion of a Trimble TANS II receiver on the test flight of a Terrier Improved Orion vehicle from Wallops Island, Va. Taking advantage of surplus space and accommodations aboard NASA Sounding Rockets in the ensuing years a number of receivers were tested and a COTS based system developed which has now been flown in excess of 20 times with a success rate of 95%.

GPS performs a number of functions on launch vehicles and payloads. Tracking of vehicles, and the resultant position, velocity and time data is used for purposes of range safety, performance analysis, determination of orbital insertion parameters and payload recovery. This is usually done with radar or optical tracking, but radars are quite complex and expensive to operate and maintain. GPS can be used to augment or replace much of the infrastructure associated with missile tracking.

**Range Safety Capabilities and Issues**

The role of GPS as a range safety tool is in its infancy, but is rapidly expanding. Depending on the type of vehicle and location of the range, many rockets are outfitted with flight termination systems that will destroy a missile that departs from its expected flight path in such a way as to endanger lives or property. Ground controllers can use position data from GPS to make this judgment or it can be implemented autonomously. Even if a vehicle has no flight termination system, it is the responsibility of the range to know its location at all times and to be able to predict the point of impact. The Eastern and Western Test Ranges will cease radar tracking within two years. The Range Commanders Council Safety Committee is currently defining requirements for qualification of GPS receivers to provide tracking data for flight termination systems.

Even when traditional methods such as radars, telemetry antennas, telescopes, and cameras are used to track rockets, they sometimes cannot be pointed to track continuously from the launch pad and occasionally they lose track. For this reason, there must exist a means of directing them to a determined location in space. These devices are networked to accept and output data, either from computer predictions or another tracking device. GPS data received in real time from the vehicle in flight can now be a source of this slaving data.

**GPS Accuracy**

GPS is capable of simultaneously tracking multiple vehicles or payloads much more accurately and efficiently than traditional methods such as radar. GPS can also be used to very precisely time tag data samples allowing them to be correlated with other data or used for interferometric measurements.

Precise position, velocity and time (PVT) are often necessary for evaluating the scientific data. Extremely accurate time from GPS can be used to time stamp the housekeeping and science data. It has been demonstrated that the precision of data time tagging can be increased a thousand-fold over the common method of tagging the data on the ground as received. [7] The time of payload events such as a shutter opening, boom deployment or the saturation of a sensor can be similarly established. Similarly, events such as deployments, course changes and flight termination can be triggered by the PVT data.

**GPS System Architecture**

New Mexico State University Physical Science Laboratory (NMSU/PSL) designed the antenna to WFF specifications. It consists of eight right hand circularly polarized radiating elements fabricated on two 1/8" thick by 5.5" width half rings which are joined together and flush mounted in a groove milled into the skin of the rocket's payload section. The two sub-arrays are fed in-phase with a coaxial power divider harness. A radome is incorporated into each subarray to protect against heat. The pattern is fairly circular with -8dBic at 90% full coverage. Due to the elements being fed in-phase, a null of 3 to 5 dB at the 3dB down level exists along the axis of the rocket. The VSWR is approximately 2 with a bandwidth of about 10 MHz.

The combined signal from the antenna is routed to a Trimble preamplifier that provides 42dB of gain. Power for the preamplifier is provided via the coaxial cable. The frequency range is 1565 to 1585 MH with excellent rejection of out of band signals.

The receiver consists of two printed circuit boards. One board is the Ashtech G12 HDMA GPS engine manufactured by the Magellan Corporation and the other, designed and built at WFF, provides power conditioning, communications format conversion, and analog to digital conversion. Both the boards are integrated into a 3" x 5" x 1" aluminum box with a single 25 pin D connector and an SMA RF connector. Even filled with a plastic potting solution to stabilize the boards against vibrations, the receiver weighs only a few ounces.

The G12 HDMA is a 12 channel L1 C/A code receiver which features wide tracking loops to accommodate the high Doppler rate involved in missile launches, low data latency, rapid acquisition of lock and is capable of outputting at up to a 10 Hz update rate. A highly stable and accurate 1 PPS signal is available for time tagging and synchronization of other payload data. Data is output as a serial RS422 stream. Parameters such as signal level and elevation masks, tracking loop bandwidths and satellite exclusion are selectable and a variety of data formats are available. In addition to position, velocity and time, pseudorange data and carrier phase information is included and may be used on the ground to calculate a highly accurate differential solution. An onboard memory saves almanac data and operating parameters in order to avoid programming in the field.

A waiver is granted to NASA as U.S. Government agency to allow operation of the receiver above the 1000kt, 60,000 ft altitude limit imposed by the International Trade in Arms Reduction (ITAR) act restrictions.

Real time differential tracking with the system is accurate to less than 10m real time with post mission processing better than 1m. Velocity accuracy is better than 1 m/s real time and up to 10 cm/s post processed. Precision of actual post processed flight data has been shown to be 4 cm [8].

## Challenges

**Antenna Development**

The antenna for attitude controlled satellites is zenith oriented with roughly hemispherical coverage with 0 dBi gain. However, it is typically optimized for lower gain (-3 dBi) at zenith and higher gain at the horizon (0 dBi). A satellite that is not attitude controlled requires an omni directional antenna. The antenna requirements can be stated as + 27 dBm EIRP is required for transmit and a minimum – 20 dB G/T for receive. The transmitter in-band power is limited by regulations to 2 Watts EIRP and LEO satellite constellation providers require control of the transmitter power and require that you use their modem that contains the transmitter and transmitter power control. Environmental testing of the commercial units for qualification for flight appears to be the most cost effective solution and is the one chosen by WFF.

No development is required for aircraft, UAV or balloon applications because these antennas are available from several aircraft antenna manufacturers. Sounding rocket wraparound antennas were developed for WFF by PSL and can also be designed and provided by WFF personnel. Commercial GPS, telemetry satcom, and many other wraparound antennas are also available. The wraparound design is very similar to GPS wraparound antennas for transmit and to telemetry S-band antennas for receive.

**Doppler Rates and Environmental**

The satellites are primarily repeaters with the Doppler acquisition and tracking requirements met by the demodulation equipment at the gateways. The design goal was to operate with differential Doppler rates up to 3 kHz. Tests are scheduled at WFF using a dual local oscillator (L.O.) frequency translator with one L.O. as a sweep generator. This dual L.O. translator will allow us to measure the differential Doppler capability of the communication system before the first test flight. The test program has proven excellent for UT operation.

## Small Satellite Application

The Flight Modem offers many significant cost advantages including reduced spacecraft communications equipment, and on-board recording. The size and power of the telemetry transmitter, command receiver, and high performance transmit antenna are reduced to a 7.5”Lx3.5”Wx1”H modem card and a hemispherical or omni antenna. Operations costs are reduced to a $0.99/per minute rate as compared to the average $300/satellite pass for recovering S-band data from LEO spacecrafts. Scheduling does not require conflict resolution inherent to ground station capability to track a single spacecraft. Securing a dial-up connection through the Globalstar network is enough to begin data flows. Down range trackers (i.e. radars and telemetry antennas) are no longer required since IP communications are widely available. Complexity is reduced to a personal computer and an Internet connection. Link margin is not an issue since the data rate limit and coverage of the Globalstar LEO satellite constellation has been defined thus reducing TT&C mission planning. However, there are limitations to the flight modem operations that must be considered.

Proposed scheduling requirements are to establish an IP connection through the LEO constellation every 2 minutes or other selected interval since communications availability will be much higher than with ground stations. Use of store and forward commands and playback recorded downlink data has eliminated the need for all but a few ground stations. For time critical or real-time communications the 2-line orbital element sets for the LEO satellites are available at http://celestrak.com/NORAD/elements/ with service in transition in December 2000 to ftp.celestrak.com for free ephemeris downloads to determine exact times of communications availability.

Since the communications system availability is greater than a ground station (compare a 20 minute ground station view of a satellite every 90 minutes to 60 minutes of view on every 90 minute orbit) then less recording time is required on the satellite. Launch rated equipment does not require the intensive space qualification of space flight rated equipment. Launch equipment could therefore be replaced with the lower cost Flight Modem. This is particularly true for sounding rockets that achieve altitudes of several hundred kilometers.

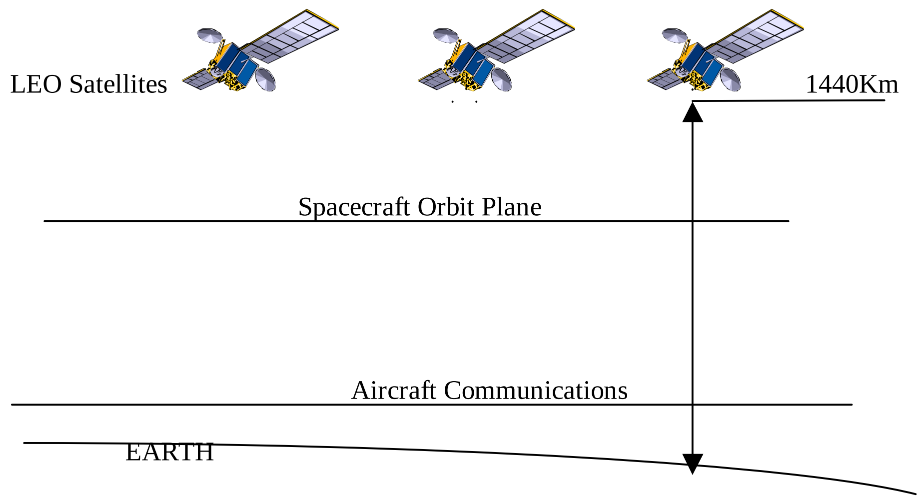


Figure #12 – Spatial Coverage of LEO Constellation

The Globalstar LEO constellation altitude is 1440km and is designed for continuous communications with commercial airliners. Gaps in coverage occur between the Globalstar constellation and lower altitude spacecraft. The gaps increase as the spacecraft increases in altitude (See Figure #12). Most spacecraft record data on-board then dump the contents at higher rates when in view of a ground station. Continuous communications is not a requirement. The LEO constellation coverage is greater than multiple line of site (LOS) ground systems. A typical spacecraft will have 20 percent of the day coverage for a single ground station. However, a LEO constellation will cover 70 percent or more of the day.

## **Summary**

A three-phased progression of test platforms (terrestrial, aircraft, and sounding rockets/balloons) enabled RF link quality and data throughput testing. Phase I determined latency measurements of less than 25ms for all receiving equipment, gateway, Internet, and satellite delays. An automated software dialup program to the LEO constellation was established to enable remote operations. Phase I determined the in and out of band emissions relative to the NRAO frequencies that overlapped into the transmit frequency from the UT to the LEO constellation. Phase I enabled testing of duplex communications between the UT and the LEO constellation. A continuous BER of 0 errors and 0 frame dropouts was measured during Phase I anytime a socket connection was established. Phase I introduced testing with a data enabled tri-mode phone, car kit, and antenna enabling testing before the OEM satellite packet modem became available. Phase II moved testing to an aircraft platform whereby BER testing continued. Application of GPS and Sea Surveillance Radar (SSR) data will test for vehicle location and low bandwidth telemetry aircraft missions. Phase III places the testing platform on a sounding rocket. Doppler shift, wraparound antenna design and a high dynamic environment will reveal how well communications are maintained by measuring received satellite signal strength, frame dropouts and loopback BER from the UT to the gateway and back. These progressive phases of test platforms will enable a structured measurement of performance and reliability.

The cost advantages of leveraging existing COTS commercial hardware with an existing commercial satellite IP data network significantly reduce ground systems and operation costs for low bandwidth (<9600bps) OTH data communications. The cost of operating the flight modem using commercial COTS satellite technology was 10% of the average cost reported by NASA's SOMO customer price list for non-government user's [9] for tracking one telemetry downlink for a typical 30 minute launch support activity.

A cost savings of 90% is realized for operations. The cost of operations is an on demand service whereby costs are only initiated once an IP connection is made. The user does not incur costs for down range antenna shipping, equipment materials or schedule conflicts. The Satellite Packet Data Modem is one of the first OEM IP COTS data products that enable duplex OTH data communications for an existing commercial LEO constellation.

## Acknowledgements

Mr. Thomas J. Pittman from NASA/GSFC/WFF Code 584 provided much of the vision for this project and campaigned to secure funds through the ARTI development effort. The Flight Modem today is a product of his vision for bridging IP satellite technology of today with commercial and governmental partnerships of tomorrow. Mr. Richard Chapman from the Tyndall AFB 53rd Weapons Evaluation Group (WEG) provided the opportunity for aircraft flights using the E-9A. Mr. Randy Albertson from the Airborne Science Directorate office located at Dryden Flight Research Center has provided an opportunity to test the satellite packet modem on board an ER-2 from Dryden Flight Research Center to the Wallops Flight Facility. Many thanks to our team for the long hours and continued commitment to advance over the horizon communications (OTH) to the next generation of Internet protocol (IP) satellite communications.

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